EVAPORATION OF WATER FROM POOLS

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ABSTRACT

Evpaoration of water from pools into quiescent air occurs in many situations The rate of evaporation in such cases is usually calculated using an empirical formula suggested by Carrier. In view of its importance, a closer look at this process of simultaneous heat and mass transfer in both laminar and turbulent free convection is indicated. This paper presents a correlation based on experiments for evaporation in laminar free convective flow.

Key words: Evaporation, Mass Transfer in Natural correction.

INTRODUCTION

One of the ways of utilising Solar Energy is to use it in maintaining the interior temperatures of buildings at comfortable levels in all seasons of the year. Both cooling and heating of buildings can be achieved, as required, by solar energy. A novel method of cooling the interiors in summer and heating them in winter by the use of water ponds on roofs fitted with sliding covers has been described in refs. 1 and 2. As these authors point out, this aspect of solar energy utilisation is of particular significance to the developing countries of the world. Interior cooling by ' Solar Air-conditioning ' is probably of greater importance than solar heating in many of these countries.

Solar Air-conditioning depends for its performance entirely on the rate of evaporation of water from the roof-pond. The rates of evaporation from pools of water in still air is calculated using one of a few empirical formulae available for the purpose. The most commonly used among them appears to be that proposed by Carrier [2, 3] as:

$$\mathring{m}'' = 0\cdot093\,(e_0 - e_\infty) \qquad \frac{lbm}{Hr.\,Ft^2}\,. \tag{1}$$

In view of its importance, it is worth taking a closer look at the method of evaulation of the evaporation rates from pools.

Theoretical Analysis

Water in a pool evaporates when exposed to air which is at a temperature above its dew point. The difference in the mass concentration of water vapor between the water surface and the ambient air causes mass transfer. The process is generally one of simultaneous heat and mass transfer as it is in a non-isothermal binary system. The water in the pool assumes a temperature a few degrees below the dry bulb temperature and the heat of vaporisation of the water that evaporates is supplied by the ambient air and other surfaces in contact with the pool water.

In still air, heat and mass transfer occur between the pool and the ambient air by free convection. Invoking the similarity between the two transport processes, one can write:

$$Sh = C_1\,(Gr_M \cdot Sc)^n \tag{2}$$

similar to $Nu = C_2\,(Gr_H \cdot Pr)^n$ in heat tranfer.

The Grashof Number in mass transfer — Gr_M is given by (4)

$$Gr_M = \frac{g\gamma\,(C^*_{W_0} - C^*_{W\infty}\,L^3}{\nu^2}$$

where γ is an 'expansion coefficient' defined by

$$\gamma = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial C^*_W}\right)_p$$

As shown in Appendix, both Gr_M and Gr_H are approximately equal to

$$\frac{g\left(\frac{\rho_\infty - \rho_0}{\rho_\infty}\right)L^3}{\nu^2}$$

where the density difference is created by differences in either the mass fraction of water vapor or temperature respectively.

In the present case, however, the variation due to temperature of air density far outweights its variation due to the presence of water vapor as the mass fractions of water vapor involved are very small. For both the heat and mass transfer processes occurring simultaneously then, we can substitute for the driving force as represented by the Grashof Number

$$Gr = \frac{g\left(\frac{\rho_\infty - \rho_0}{\rho_\infty}\right) L^3}{\nu^2}$$

and write equation (2) as:

$$Sh = C_1 \, (Ra_M)^n \tag{3}$$

or

$$\left(\frac{h_M \cdot L}{D}\right) = C_1 \left[\frac{g\left(\frac{\rho_\infty - \rho_0}{\rho_\infty}\right) \cdot L^3}{\nu D}\right]$$

EXPERIMENTAL WORK

The evaporation rates of water into still air from shallow pans of different sizes were measured. The pans were kept on sensitive balances in a large room with all its openings closed and the loss in weight was recorded at regular intervals. Simultaneously, the dry and wet bulb temperatures in the room and the pan water temperatures were recorded so that the parameters in equation (3) could be evaluated.

RESULTS AND DISCUSSIONS

The experimental results are shown in Fig. 1. Seven different sizes of water pan were tried and the points on Fig. 1 represent the averages of about six hourly readings in each case. The straight line in Fig. 1 represents the equation

$$Sh = 0 \cdot 45 \, (Ra_M)^{0 \cdot 25}. \tag{4}$$

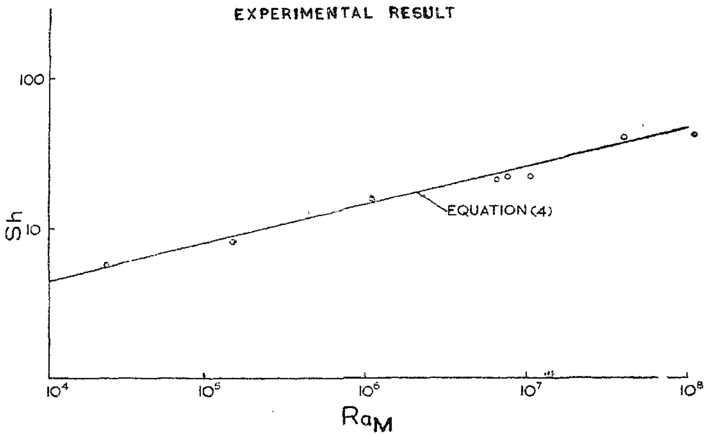

Fig. 1.

A similar relation $Nu = 0 \cdot 27\ (Ra_H)^{0 \cdot 25}$ has been proposed for heat transfer by natural convection in laminar flow from a cooled horizontal surface facing upwards [5]. It is stated that in this case the convective flow remains laminar even upto $Ra_H = 10^{10}$ [6]. It is reasonable therefore to expect that, with water evaporating to still air, the flow remains laminar until Ra_M exceeds 10^{10}. In the present experiments, pans large enough to result in Rayleigh Numbers of this magnitude could not be handled because sensitive balances in the higher range were not available.

Conclusions

It is obvious that the empirical relation (1) oversimplifies the problem of evaporation of water from pools into still air.

In the laminar range ($Ra_M < 10^{10}$) equation (4) can be used to determine the evaporation rate in free convection. This, however, requires a knowledge of the water surface temperature. If there is no other source of heat transfer to the water except the air itself, the water temperature can be estimated by the heat-balance relation

$$h_M \cdot (C_{W_0} - C_{W_\infty}) \cdot H_{fg} = h\,(t_\infty - t_0)$$

Such, however, is rarely the case in practice.

In the laminar range, the mass flux of water from the surface varies as $L^{-1/4}$ where L is a characteristic dimension of the pool. In the turbulent regime, however, the mass flux may be expected to be independent of L as the relation

$$\bar{Sh} = C_3 (Ra_M)^{1/3}$$

may be expected to hold in that regime. Equation (1) can be applied, if at all, for the turbulent free convection.

It would be interesting to explore the turbulent flow regime as large pools ensure a high enough Ra_M for turbulent convection to occur.

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NOTATION

C_1. C_2, C_3 = Constants (Dimensionless)

C_W = Mass Concentration of Water Vapor (Mass/Vol.)

C_W^* = Mass Fraction of Water Vapor (Dimensionless)

D = Mass Diffusivity

e = Partial Pressure of Water Vapor, Inches of Mercury

Gr = Grash of Number

Gr_M	=	Mass Transfer Grashof Number
Gr_H	=	Heat Transfer Grashof Number
h	=	Heat Transfer Coeficient
h_M	=	Mass Transfer Coefficient
H_{fg}	=	Heat of Vaporisation
k	=	Thermal Conductivity
L	=	Characteristic Dimension of Pool
$\overset{o}{m}''$	=	Mass Flux [Mass/(Time $\times$ Area)]
Nu	=	Nusselt Number $= \frac{hL}{k}$
Pr	=	Prandtl Number $= \nu/\alpha$
Ra	=	Rayleigh Number
Ra_M	=	Mass Transfer Rayleigh Number $= g\gamma\,(C^*_{W0} - C^*_{W\infty})\,L^3/\nu D$
Ra_H	=	Heat Transfer Rayleigh Number $= g\beta\,(t_0 - t_\infty)\,L^3/\nu\alpha$
Sc	=	Schmidt Number $= \nu/D$
Sh	=	Sherwood Number $= \frac{h_M . L}{D}$
t	=	Temperature

Greek Symbols—

α	=	Thermal Diffusivity
β	=	Thermal Expansivity $= -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p$
γ		Expansion Coefficient $= -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial C^*_W}\right)_p$
ν	=	Kinematic Viscosity
ρ	=	Density

Subscripts:

0:	=	Indicates Values at Water Surface
∞;	=	Indicates Values in Ambient Air.

APPENDIX

$$\gamma = \text{Expansion Coefficient} = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial C_W^*}\right)_p$$

At constant pressure

$$\gamma \int_0^\infty dC_W^* = -\int_0^\infty \frac{d\rho}{\rho}$$

$$\gamma\,(C_{W_0}^* - C_{W\infty}) = ln\,\frac{\rho_\infty}{\rho_0} \approx \frac{\rho_\infty - \rho_0}{\rho_\infty}$$

$$\left[ln\,x = \left(\frac{x-1}{x}\right) + \frac{1}{2}\left(\frac{x-1}{x}\right)^2 + \ldots\right]$$

$$Gr_M = \frac{g\gamma\,(C_{W0} - C_{W\infty}^*)\,L^3}{\nu^2} \approx g\left(\frac{\rho_\infty - \rho_0}{\rho_\infty}\right) L^3/\nu^2$$

Similarly,

$$\beta = \text{Thermal Expansivity} = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p$$

and

$$Gr_H = \frac{g\beta(T_0 - T_\infty)\,L^3}{\nu^2} \approx g\left(\frac{\rho_\infty - \rho_0}{\rho_\infty}\right) L/^3\nu^2$$